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Recently derived necessary conditions, and related sufficient conditions, suggest that adaptive control can be used for systems having nonlinear and/or flexible, potentially extending adaptive control far beyond the existing scenarios. This report documents research in adaptive stabilization of certain infinite dimensional linear systems in state space form and an extension to the stabilization and control of distributed parameter systems, modelled as boundary value systems, using point actuators and sensors. Research on nonlinear stabilization and control is also described leading to the formulation and partial solution of feedback stabilization about attractors as both an important extension of classical equilibrium analysis and as an important tool in more sophisticated control tasks such as asymptotic tracking and disturbance rejection.

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1. **Summary** During the period July 15, 1986–July 14, 1987, we made advances principally in three proposed research objectives: The rigorous, detailed development of necessary conditions for adaptive stabilization, the design and analysis of explicit adaptive algorithms whose existence is guaranteed by the consequent "principle of adaptive stabilization," and the longer range objective of extending the scope of applicability of dynamic compensation-based adaptive control to systems containing nonlinear elements and/or flexible components.

During the period July 15, 1987–July 14, 1988, we used this "principle of adaptive stabilization" as a tool for designing low order dynamic compensation based adaptive controllers for certain infinite dimensional systems, modelling flexible or distributed parameter systems (DPS). Our preliminary work in this area contains a rigorous analysis of proportional error adaptive controllers in a Hilbert space setting, while our most recent work develops the rigorous analytic basis of a frequency domain control approach to stabilization of DPS in a more natural realization as a boundary value problem. This provides a foundation for dynamic compensation based adaptive control of DPS using point actuators and sensors, interpreted as boundary conditions. For nonlinear systems, we have further developed our preliminary program giving methods for analysis and design of nonlinear feedback systems. In particular, based on several specific applications, including the stabilization of rigid spacecraft about a principal axis, the problem of feedback stabilization about attractors was recognized as being crucial for design problems involving more sophisticated tasks such as tracking, bounded-input, bounded-ouput stabilization, etc. Our recent work on this new problem area has focused around a nonlinear enhancement of root-locus theory, which uses methods from nonlinear dynamics in an essential way.

2. **Proposed Research** The research program described in AFOSR Grant 85-0224 consisted of a 2-year effort, July 15, 1986–July 14, 1988, based on an initial one year effort on the design of dynamic compensation-based adaptive controllers. The initial research effort had focused on designing low dimensional adaptive control schemes by directly tuning the parameters of classical controllers, and on the issue of clearly delineating the scope of applicability of adaptive control, i.e., the derivation of necessary conditions for the existence of adaptive controllers in given contexts. Encouraged by an unanticipated success, especially in the partial development of nearly complete necessary and sufficient conditions for a restricted class of adaptive stabilization problems, the present proposal contained the following specific research objectives:

(1) The explicit controller design of simple dynamic compensation based schemes for stabilizing classes of linear systems, where existence is guaranteed by general necessary and sufficient conditions. Important new areas include adaptive stabilization of multi-input multi-output systems.

(2) The rigorous development of necessary conditions for adaptive stabilization in the nonequilibrium case, i.e., when the closed-loop system has continua of equilibria, center manifold dynamics, etc., as well as a clear, intuitive system theoretic interpretation of such necessary conditions.

As longer term goals, we cited:

(3) The extension of these design techniques to more practical systems, which include rigid nonlinear (and ultimately flexible) components, enhancing the intrinsic ro-

bustness of these controllers.

(4) The design of dynamic compensation-based adaptive controllers achieving other important control objectives, such as asymptotic tracking.

3. **Status of Research** During the first year, July 15, 1986–July 14, 1987, of this two-year effort, our main research was focused especially on tasks (1)–(2) in our statement of Research Objectives.

In particular, we developed a rigorous proof of the following general necessary condition for adaptive stabilization of a class Σ of linear processes σ by a finite dimensional nonlinear controller: There exists a dimension $q \geq 0$ such that for each fixed $\sigma \in \Sigma$ there is some linear compensator of dimension q for which the associated closed-loop system has all its poles in the closed left half plane. The existence of such a q such that all closed-loop poles can be assigned in the open left half plane was shown by Martensson to be sufficient and, taken together, these assertions give us a "principle of adaptive stabilization" precisely quantifying the a priori information required about a process for stabilization in an adaptive context.

This principle guarantees the existence of explicit adaptive stabilization schemes in scenarios previously regarded as beyond the scope of adaptive control, including in particular the adaptive stabilization of multi-input, multi-output linear systems, of nonlinear systems and, as several simulations have suggested, of infinite dimensional systems such as systems containing flexible components or having significant transmission characteristics. This research objective is one of the principle components of tasks (1) and (3) and Publication 2 gives an explicit algorithm for stabilization of certain infinite dimensional minimum phase systems. Significant here is that stabilization is achieved by a low dimensional controller and can be modified so as to not require explicit knowledge of the "interactor" matrix. These results are couched in the setting of Hilbert space, e.g. rigged Hilbert space, realizations of distributed parameter systems and an important tool for both tasks (3) and (4) is the development of comparable stabilization schemes derived in terms of a more natural description of a DPS as a boundary value problem, allowing for the modelling of point actuators and sensors in terms of boundary conditions. Some very promising results in this direction have been reported in publication 2, which gives a fairly general extension of root-locus techniques in the setting of non self-adjoint boundary conditions, relying on fundamental work of Birkhoff, Cramer and Stone. We are also optimistic that these methods will provide the theoretical underpinnings of our effort in task (4), the design of relatively low dimensional controllers achieving adaptive tracking and adaptive regulation for certain distributed parameter system. We expect such schemes to include a certain amount of parameter identification and stochastic realization and Publications 6 and 8 contain our initial results on the solution of the related partial stochastic realization, or covariance extension, problem which also has important applications in signal processing.

Another aspect of Task 3 in which we have had considerable success is in the control of nonlinear systems. In contrast to the classical linear finite dimensional case, which is fairly well understood, a preliminary to nonlinear adaptive control is the development of systematic methods for asymptotic stabilization near equilibria, asymptotic tracking, observer design, etc. Publication 4 contains research on the fundamental problem of nonlinear observability using methods from nonlinear dynamics and geometry. Publications

1 and 7 contain the foundations of our "frequency domain" approach to nonlinear feedback stabilization, using nonlinear dynamics to obtain nonlinear enhancements of classical root-locus theory. These techniques have allowed us to solve several specific outstanding problems, including problems on the feedback stabilization of rigid spacecraft, as reported in Publication 10, and can be modified so as to obtain stabilizing feedback laws which are robust with respect to unmodelled dynamics (see Publication 13).

In publication 3, we extended these feedback design techniques obtaining feedback laws which would simultaneously achieve disturbance decoupling of an output variable from a state dependence disturbance channel. The example of a coupled harmonic oscillator, modelling for example an electrical power system, together with our solution of the feedback stabilization of a rigid spacecraft about a principal axis led to the realization that an essential feature of feedback stabilization, in the more important sense of bounded input, bounded output stabilization, consists in designing feedback laws which stabilize the closed-loop system about an attractor, vastly generalizing the previous equilibrium cases. Our initial analysis and simulations of this important new problem area is reported in Publications 9 and 10, in which we provide rigorous convergence analysis in the context of a nonlinear root locus theory couched, however, in the language of nonlinear dynamics.

Finally, one very important aspect of the controller schemes we have designed, both in the linear and in the nonlinear cases, is the kind of information which is or is not required. Very much in the spirit of the principle of adaptive stabilization, these schemes do not always require knowledge of an upper bound on the system dimension and, in fact we have shown that some of the linear schemes continue to function in infinite dimensions. This suggests that in addition to nonlinear rigid elements it may be possible to design controllers for systems having flexible components or distributed parameters, for distributed parameter systems, as will likely be required in an effective solution of feedback design problems in flow control.

4. Cumulative Chronological List of Publications (July 15, 1987–July 14, 1988)

1. Analysis and Design of Nonlinear Feedback Systems (with A. Isidori), accepted subject to revision by *IEEE Trans. Aut. Control.*
2. Adaptive Stabilization of Infinite Dimensional Linear Systems, *Proc. 26th IEEE Conf. on Dec. and Control*, Los Angeles, 1987.
3. Nonlinear Disturbance Decoupling with Stability (with A. Isidori), *Proc. 26th IEEE Conf. on Dec. and Control*, Los Angeles, 1987.
4. On the Topology and Geometry of Universally Observable Systems (with C. F. Martin and W. P. Dayawansa), *Proc. 26th IEEE Conf. on Dec. and Control*, Los Angeles, 1987.
5. Linear Model Matching with Prescribed Tracking Error and Internal Stability for Nonlinear Systems (with R. Castro and A. Isidori), *Analysis and Optimization of Systems*, Springer-Verlag, 1988.
6. An Algebraic Description of the Rational Solutions to the Covariance Extension Problem (with A. Lindquist), *Linear Circuits, Systems and Signal Processing*, North-Holland, 1988.
7. New Results and Counterexamples in Nonlinear Feedback Stabilization (with A. Isidori),

to appear in *Systems and Control Letters.*

8. On the Kimura-Georgiou Parameterization of Rational Modelling Filters (with A. Lindquist), to appear in *Int. J. Control.*

In preparation:

9. Nonlinear Feedback Design from the Zero Dynamics Point of View (with A. Isidori), to appear in *Proc. of Conference on Computation and Control.*
10. Feedback Stabilization about Attractors and the Problem of Asymptotic Disturbance Rejection (with A. Isidori) to appear in *Proc. of 27th IEEE Conf. on Dec. and Control.*
11. Analysis and Simulation of a Controlled Rigid Spacecraft: Stability and Instability Near Attractors (with A. Isidori, S. Monaco, and S. Sabatino) to appear in *Proc. of 27th IEEE Conf. on Dec. and Control.*
12. Asymptotic Behaviour of Root-Loci for Distributed Parameter System (with D. S. Gilliam), to appear in *Proc. of 27th IEEE Conf. on Dec. and Control.*
13. Robust Stabilization of Nonlinear Systems (with X.-M. Hu and A. Isidori), to appear in *Proc. of Conf. on Computation and Control.*

5. University Personnel Contributing to the Project,
"Dynamic Compensation-Based Adaptive Control"

Dr. C. I. Byrnes, Research Professor of Engineering and Mathematics, Departments of Mathematics and of Electrical and Computer Engineering

Mr. S. Pinzoni, graduate student in Department of Electrical and Computer Engineering

6. Seminars, Colloquia and Oral Reports

September 1987	Nonlinear Disturbance Decoupling with Stability, Department of Mathematics, Texas Tech University
November 1987	Attitude Stabilization and Control of Rigid Spacecraft, Department of Electrical and Computer Engineering, University of Texas–Austin
December 1987	Attitude Stabilization and Control of Rigid Spacecraft, 3rd Southwest Symposium on Systems and Control, Arizona State University
	On the Topology and Geometry of Universally Observable Systems, 26th IEEE Conference on Decision and Control, Los Angeles
	Nonlinear Disturbance Decoupling with Stability, 26th IEEE Conference on Decision and Control, Los Angeles
	Adaptive Stabilization of Infinite Dimensional Linear Systems, 26th IEEE Conference on Decision and Control
January 1988	Adaptive Stabilization of Infinite Dimensional Linear Systems, Department of

	Optimization and System Theory, Royal Institute of Technology, Stockholm
February 1988	Disturbance Decoupling for Nonlinear Control Systems, Dept. of Mathematics, University of California, San Diego
	Nonlinear Disturbance Decoupling with Stability, Dept. of Mathematics, University of California, San Diego
March 1988	Stabilization and Control of Nonlinear Systems, Mathematics Institute, Oberwohlfach, West Germany
April 1988	Uniform BIBO-Stabilization of Nonlinear Systems, Dept. of Mathematics, Texas Tech University
May 1988	Stabilization and Regulation of Nonlinear Control Systems (3 lectures), Department of Optimization and Systems Theory, Royal Institute of Technology, Stockholm
June 1988	Linear Model Matching with Prescribed Tracking Error and Internal Stability for Nonlinear Systems, INRIA Conference on Analysis and Optimization of Systems, Antibes
	Exact and Asymptotic Tracking for Nonlinear Systems, Conference on Nonlinear Control, Nantes

7. **Significant New Discoveries** During the period July 15, 1986–July 14, 1987, we made significant discoveries on two fronts. First, we rigorously extended our previous necessary conditions for adaptive stabilization to the more prevalent situation where the closed-loop adaptive system can have non isolated equilibria. In fact, our methods, drawn from nonlinear dynamics, suggested that similar conclusions–perhaps even the consequent "principle of adaptive stabilization"–will hold for systems containing flexible components.

Second, preliminary to the adaptive control of nonlinear systems, the development of a systematic approach to the analysis and design of nonlinear feedback systems for achieving various control objectives, such as stabilization, tracking, etc., is required. During the period July 15, 1986–July 14, 1987, we sketched the development of a systematic framework, enhancing linear "frequency-domain" approaches and giving fairly general stabilizing feedback laws for broad class of nonlinearities.

During the present reporting period, July 15, 1987–July 14, 1988, we made some important advances in each of these arenas. Concerning the first area, we were able to give a rigorous convergence proof for adaptive stabilization of certain infinite dimensional systems, modelling for example a distributed parameter system as a system evolving on a ("rigged") Hilbert space, yielding a significant extension of traditional, finite dimensional adaptive control. It is highly desirable, however, to be able to stabilize and control distributed parameter systems using point actuators and sensors and to have an intuitive design procedure based on a more natural description of the system as a boundary value problem. In this year we have obtained some general "frequency domain" methods for non-self adjoint boundary value problems using, in lieu of spectral theory, certain classical analytic methods pioneered by Birkhoff, Cramer and Stone. In particular, we are able to design, and give a rigorous analysis of, stabilizing proportional error and PD controllers for very natural heat conduction and wave propagation control problems.

In nonlinear control, we have discovered and begun researching a new, and, we feel, very significant problem which is genuinely nonlinear, having no linear analogue. Based on several examples, including the control of coupled harmonic oscillators and a longstanding problem involving the stabilization of a rigid spacecraft about a principal axis, we discovered that the problem of feedback stabilization about an attractor–vastly generalizing the standard equilibrium case–is an extremely important tool in more sophisticated control design problems, such as tracking, bounded-input bounded-output stabilization. We are presently developing, in joint work with Alberto Isidori, a nonlinear enhancement of root-locus theory, using nonlinear dynamics in an essential way, yielding positive results on this problem for broad classes of nonlinear systems.